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Transonic Flow Visualisation using Holographic Interferometry.

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Over the past ten years experiments have been conducted with the objective of extracting useful fluid dynamic information from holograms. The fluid being studied has been air and its compressibility, at transonic speeds, measured interferometrically.

The type of problems to which holography has been found applicable at transonic speeds are:-

1. Axial Gas Turbines.

1.1 First stage compressor shock system.

One of the major optical measurement success has been the use of holography to visualise the leading edge shock structure on transonic compressors. This work was started by several groups in the late sixties, [1]. Their attempts to develop the method were limited by the quality of the lasers used and the test facilities available. Since then Rolls-Royce UK have taken the method and applied it to commercial gas turbine compressor problems. It is currently used to test each new compressor [2].

A typical first stage transonic compressor fan can be as large as 2m in diameter, figure 1, with the shock structure existing over two thirds of the blade height. The holographic system uses a ruby pulse laser to visualise this leading edge shock structure in three dimensions. The virtue of this method is speed, taking no more than 4hrs of rig running to map all the blades for 4 characteristic points on a performance curve. Approximately 200 holograms are made during each test. These are examined to select particular blade passages for more detailed study with LDA. Normally, the detailed LDA measurements take up to 40hrs of further rig running. Current data reduction in this area is achieved by logging the holographic data manually into a computer and then using 3 dimensional plotting packages to illustrate the shock position.

A detailed description of the method has been made in [2]. However for this part of the paper a simplified account will be made.

The output beam from a pulse laser is divided into two parts. One forms the reference beam the other the object beam, figure 2. The method can be used because of the type of laser currently available. The coherence length of the ruby pulse laser is of the order of 1 metre, making it possible to form holograms without contour fringes of objects up to 3 metres across. As a result it is possible to expand a laser beam to reflect from the inside surface of a gas turbine of 4 square metres. This illuminated area forms the background against which the shock structure can then be viewed. The second feature of the laser is that it can produce two such pulses of the same frequency and spatial coherence length, ie 'clean' , non-contoured holograms 95% of the time.

The sample beam illuminates the inside of the casing of the engine directly ahead of the rotor. From a view point just over the rotor it is possible to see between the passing blades the upstream illuminated area.

The air just ahead of the shock has a density lower than that just after the shock. If two holographic exposures are made (approximately 2 microseconds apart) then two holograms are made on the same piece of film. The only difference between the holograms being the movement of the shock as it passes the viewing window, figure 3. It is this difference in shock position and its overlap between the two exposures in the hologram, which is visualised as an optical phase shift. Such a shift makes the position of the shock apparent as a dark or bright area in the reconstructed hologram as shown in figure 4.

1.2 Modal vibration of fans.

Holography has also found application in the modal vibrational analysis of the compressor fans. This is done regularly on static fans and in a few instances on fluttering rotating assemblies, as described in [3] and [4]. For vibrational holography the digitisation of the data is far simpler, in that, the blade represents a two dimensional surface. The movement of the surface due to vibration can be calculated from the analysis of two photographic reconstructions made from two holograms of the same object at different viewing angles. However the accuracy of this stereographic reconstruction method relies on the exact location of both the object and the reconstructed hologram. It is noted, that the errors which can be generated by changing the reconstruction wavelength and by rotating the angle of analysis are not negligible.

1.3 Turbine stages

Holography is also being applied with growing success to the turbine stages of the Axial gas turbine. Starting with two dimensional cascade work discussed in [5] and now developing into a diagnostic for rotating test rigs.

An interesting situation has arisen with the development of complicated numerical prediction codes, in that, there are few well documented test cases against which they can be critically tested. Interferometric data has sufficient resolution to test the codes at the points where they are most sensitive. Currently this is the leading edge, where a comparison with an inviscid code has been made, figure 5 [6], and trailing edge of the blade, figure 6 [7]. This academic research has led to improvements in the numerical modelling of these regions and has contributed to the understanding of the turbulence modelling, essential in the development of full Navier Stokes solvers. An illustration of this is shown in figure 7 where the sidewall boundary layer separation has been predicted and compared with interferometric data. The simplest method of evaluating and interpreting data in these cases has been to scale the output contour plots of the numerically generated data to match in size the photographic reconstructions made from two dimensional interferograms [8]. The contour's heights, which then match the optically generated isodensity fringe spacings, give a sharp test of the ability of the code to model the flow.

One experimental series completed at the Whittle laboratory CUED, was designed to explore the possibility of being able to form holograms with interferometic tolerances without the need of a rigid framework. In effect the cascade walls formed the optical framework, with the pulse laser situated outside of the 2m diameter test facility. To achieve this result a drop in optical resolution has been tolerated; however it has been possible to make the following measurements. The Isodensity data shows in detail the leading edge stagnation position, the shock boundary layer interaction region, the trailing edge vortex structure and on the surface of the blade a projection of the flow distribution, figure 8. For these cases the data reduction has been achieved by hand in two stages. Firstly the data has been photographed and then the photographs digitised. The objective of this work is directed towards producing a holographic diagnostic which could be attached to a rotating test facility. Such a device could then be used to examine the stator rotor interaction and related rotor passing effects.

All the experiments have been completed with the use of a high power solid state laser. High resolution 3,000 lines per millimetre holographic film and plates have been used as the data storage material.

2. Steam Turbines.

There has been less holographic interest in steam turbines, partly due to lower funding and the lack of available test facilities. Industrial steam turbine sets also tend to be less accessible than the large aero gas turbines, which have had the external fittings pared down to meet the weight and pod mounting needs of a flying engine. One of the main difficulties is that the gas density passing through the last stage of the turbine set is sub atmospheric which makes holographic density change measurements rather insensitive. The speed of air passing through atmospherically pressured Reynolds number scaled linear and annular model steam turbine cascades is similar enough for holography to be applied to without difficulty.

The problems being addressed in this area are similar to those of the gas turbine, with the emphasis more towards understanding the high exit Mach flows and their effect on the base flow. This has been shown in the two dimensional approach developed at EPFL (Ecole Polytecnique Federale de Lausanne) for visualising the trailing edge shock structure around the trailing edge of a 30 times scaled model of a steam turbine, figure 9, [9]. The boundary layers on the object can clearly be seen followed by an isentropic Prandtl-Meyer expansion where the flow accelerates from M=1.3 upto M=1.9 figure 10. The shear flow converging to form the confluence region can also be seen in greater detail in figure 11 where the interferometric reconstruction has been enlarged to show the separation of the boundary layer at the end of the trailing edge. By adding finite fringes to the interferogram it is possible to obtain the exact location of the sonic line in the boundary layer. Figures 12 and 13 show the same trailing edge but with the sidewall liners adjusted for a subsonic outlet. In the first case, figure 12, the exit velocity is Ma.=0.61 and a classical Karman vortex street has been observed. In the second case at just sonic outlet conditions the trailing edge flow is unstable being neither the previous subsonic flow nor the fully developed supersonic exit shown in figure 10. Figure 14, made using two holographic pulses 3 microseconds apart, shows the unsteady component of the fully developed flow of figure 10. For the first time and as a consequence of the scale of this trailing edge it is possible to observe the vortex structure present in the shear layer directly after the separation point. The size and strength of this vortex structure can be seen to increase at the end of the confluence region with the influence of the downstream compression shock.

The other problems of current interest being, the effect of off condition incidence, flow separation, shock position, flutter and the effect of inserting measurement probes into the blade passage. Figure 15 is a photographic reconstruction made from a three dimensional flow visualisation of the shock structure within an annular cascade also at EPFL.

3. Boundary Layer Flow

A recent data interpretation problem has been approached using a combination of optical techniques [10]. Using a short duration pulse separation from a ruby pulse laser, it has been possible to observe a discrete and regular structure in the boundary layer. This structure which can be observed over a range of Mach numbers from just sonic, figure 16 to a Mach number of 2.5, figure 17 gives the appearance when visualised using a two dimensional interferometric approach of dark striations occurring with a spatial periodicity of the boundary layer height along the boundary layer. The striations were then measured again using a technique defined as dynamic Schlieren, described in greater detail in [11] and [12]. From these measurements; the time of flight of the striation between two optical probes placed in the Schlieren system image plane, showed them to be moving with the expected boundary layer velocity figure 18. It was also possible to find from this system the autocorrelation function. This did not indicate a regular periodicity in the flow but a strongly turbulent decay similar to that seen in hot-wire data. The third optical measurement used a three dimensional scatter plate holographic set-up. It can be seen in the resulting holograms that the seemingly periodic structure in the boundary layer is being created by a discrete bursting process. This is not unlike the method which is described by Head 'the action of vortex bursting within the boundary layer' [13]. Further the disturbances which have the appearance of a small 'explosion' have a width and height of the boundary layer. Certainly in terms of a holographic density change this implies that a significant part of the density gradient within the boundary layer being disturbed over a time period of between 3 to 20 microsecs. This would be consistent with a turbulent bursting process. The problem has taken considerable time to understand, because there was a limit in the speed by which either temporal or spatial information can be stored. In this case the three separate measurements which give the temporal and spatial data occurring during the bursting process would have been difficult to make with one single data collection system.

Holographic interferometry is also being used to visualise the supersonic flow around a corner [14]. Here the objective is to compare the 'instantaneous' density profiles obtained using holography with temporally averaged pitot static measurements and theory. Figure 19 shows a supersonic boundary on the tunnel floor, whereas figure 20 is a reconstruction made from a flow around a two dimensional compressional corner.

4 Radial Turbomachinery

Until April 1984 no holographic flow visualisation experiments had been peformed on small (100mm diameter) radial turbochargers. A typical turbocharger is shown in figure 21 with an insert photograph showing the holographic view of the compressor. These machines, which are used to boost the compression power of large truck engines, rotate at up to 80,000 revs. They can reach transonic speeds at the blade tip, and generate loss through shock waves. Using a holographic system, developed from that used previously on large axial fans, it has been possible to produce visual evidence of this shock structure.

In a second experiment described in [15] made in April 1985 the holographic system was rearranged to view the exit passage from the rotor. Again a high aerodynamic loss area has been identified. Here a vortex structure was postulated to occur as a result of backflow into the rotor passage. Laser anemometry results were obtained showing a slip factor of 1.2. Holography has been used for the first time to visualise this disturbance as shown in figure 22.

Conclusion

An account has been made of some of the applications of holographic interferomtry to the visualisation of transonic flows.

In the case of the compressor shock visualisation, the method is used regulary and has moved from being a research department invention to a design test tool. The need to speed up the data extraction from the method is still a weakness; although it is still an order of magnitude faster at collecting data than the current alternative LDA.

With the implementation of automatic processing and simple digitisation systems, holographic vibrational analysis has also moved into routine NDT testing.

The code verification interferograms have been instructive, but the main turbomachinery interest is now in three dimensional flows. A major data interpretation effort will be required to compute tomographically the three dimensional flow around the leading or the trailing edges of a rotating blade row. Holography, however is the only current technique with adequate resolution to meet this problem.

The bolt on approach shows the potential application to current unsteady flows of interest. In particular that of the rotor passing and vortex interaction effects experienced by the new generation of unducted fans. It can also provide data on the stator rotor interaction without requiring the construction of specialised facilities.

The turbocharger tests present a new area for the application of holography. The tests made have been at a preliminary level. A more detailed study should help in reducing some of the high viscous losses experienced.

Figures

1. Axial gas turbine first stage compressor fan as used in a holography test. The arrow shown, points to the 19mm diameter negative lens through which the sample beam of the ruby pulse laser was expanded. The opposite side of the casing has been painted white to diffuse and reflect the laser light.

2. Diagram showing the method by which the holographic system was applied to the first stage compressor fan during a test.

3. Diagram showing the movement of the compressor blade fan assembly between two holographic pulses.

4. Photographic reconstruction showing the shock structure at the tip of the compressor fan as visualised using holography.

5. Comparison between an interferometric measurement made of the transonic flow around an isolated aerofoil and its numerical prediction using a time marching solution.

6. Comparison between the trailing edge flow in a linear cascade measured interferometrically, and a loss predicting Navier-Stokes solver computed solution.

7. Comparison of a transonic wedge profile with sidewall boundary layer separation and a viscous numerical solution.

8. Interferographic reconstructions made from the 'Whittle Lab bolt on interferometer'. Both the leading and trailing flows can be seen clearly, with the confluence region enlarged to show the formation of the trailing edge vortex structure.

9. Diagramatic layout of the EPFL image plane ruby pulse interferometric system as applied to a two dimensional Laval nozzle.

10. Supersonic trailing edge flow showing the Prandtl-Meyer expansion of the flow from a Mach number of Ma.= 1.3 to Ma.=1.9.

11. A photographic enlargement of figure 10, showing in detail the trailing edge separation point and the formation of the exit shear layer.

12. Laval nozzle now adjusted to operate in the subsonic region. Ma.=0.6

13. Laval nozzle adjusted to operate in an unstable region neither a typical Karman vortex street or as a fully formed supersonic exit.

14. Unsteady components of the stable exit flow shown in figure 10.

15. A photographic reconstruction made from a hologram showing the shock structure within the EPFL supersonic inlet annular cascade.

16. Two holographic pulses 30 microseconds apart show a 'regular' structure within a 10mm thick boundary layer at just sonic Mach numbers.

17. Two holographic exposures made 3 microseconds apart in a supersonic (Ma.=2.5) boundary layer.

18. Velocity measurements using Dynamic Schlieren.

19. Density gradient within a supersonic boundary layer, Ma.=2.5. The interferogram was formed by taking one exposure before the tunnel ran, the other during the run on the holographic plate.

20. Density gradient within a supersonic boundary layer at a compression corner, showing the penetration of the shock.

21. Photograph showing a typical turbocharger, the inset shows the view taken in the holographic visualisation of the leading edge shock structure. In this case part of the housing has been spark eroded away and a glass window fitted. A metal mirror has also been mounted onto the turbocharger to provide an optical viewpoint perpendicular to the flow direction.

22. Reconstruction made of the exit diffuser vortex.

References

[1] Wuerker R F, Kobayashi R J, Hejlinger L D and Ware T C 'Applications of Holography to flow Visualization within Rotating Compressor Blade Rows.' NASA CR 121264 1974

[2] Bryanston-Cross P J. 'Three dimensional Holographic Flow Visualisation'. Presented September 1981 at the Symposium on Measuring Techniques in Transonic and Supersonic Cascade Flow. Lyon.

[3] Hockney B S, Ford R A and Foord C A. 'Measurement of Fan Vibration using Double Pulse Holography.' Journal of Engineeering for Power Vol 100 pp 655-668 Oct 1978.

[4] Storey P A. 'Holographic Vibration Measurement of a Rotating Fluttering Fan.' AIAA Vol 22 no 2 pp 234-241 Jan 1984.

[5] Bryanston-Cross P J, Lang T, Oldfield M and Norton R. 'Interferometric Measurements in a Turbine Cascade using Image Plane Holography'. Journal of Engineering for Power Jan 1981.

[6] Bryanston-Cross P J and Denton J. 'Comparison of a Measured and Predicted Flow around the Leading Edge of an Aerofoil'. AIAA Vol 22 pp 1025-1026 1984

[7] Dawes W N and Bryanston-Cross P J. 'A Numerical and Experimental Study of the Loss Generation in a Transonic Rotor Blade'. to be published, International Journal of Heat and Fluid Flow.' Late 1985.

[8] Bryanston-Cross P J and Dawes W N. 'Comparison of Inviscid and Viscous Computations with an Interferometrically Measured Transonic Flow.' To be published AIAA July/August 1985

[9] Bryanston-Cross P J, Beretta-Piccoli F and Ott P. 'Implementation of the Ruby Pulse Laser Holography System at the LTT/EPFL.' Internal report LTT-TM-16-84. Ecole Polytechnique Federale de Lausanne Sept 1984.

[10] Bryanston-Cross P J, Edwards J and Squire L. 'Measurements in an Unsteady Two Dimensional Shock/Boundary Layer Interaction.' Presented at the IUTAM Unsteady Aerodynamics Conference, Jesus College Cambridge Sept 1984

[11] Bestwick T. 'The Structure of Turbulence in Supersonic Boundary Layers.' CUED final year project report April 1984.

[12] Bryanston-Cross P J, Camus J-J and Richards P. 'Dynamic Correlation of a Schlieren Image in a Transonic Airflow.' Published in 'Photon Correlation Techniques in Fluid Mechanics', Springer-Verlag Series in Optical Sciences Vol 38 pp 270-275 1983.

[13] Head and Bandjopadhyay. 'New Aspects of Turbulent Boundary Layer Structure.' JFM Vol 107 pp 297-338 1981.

[14] Liu X. 'Holographic Interferometry, Measurements of Shock/Boundary Layer Interaction at a Compression Corner.' CUED internal first year PhD report April 1984.

[15] Bryanston-Cross P J. 'A Holographic System for Visualising a Vortex Structure in a Turbocharger'. Presented at the meeting of Holographic Measurement, Speckle and Allied Phenomena at the CEGB headquarters London April 16th to 17th 1985.

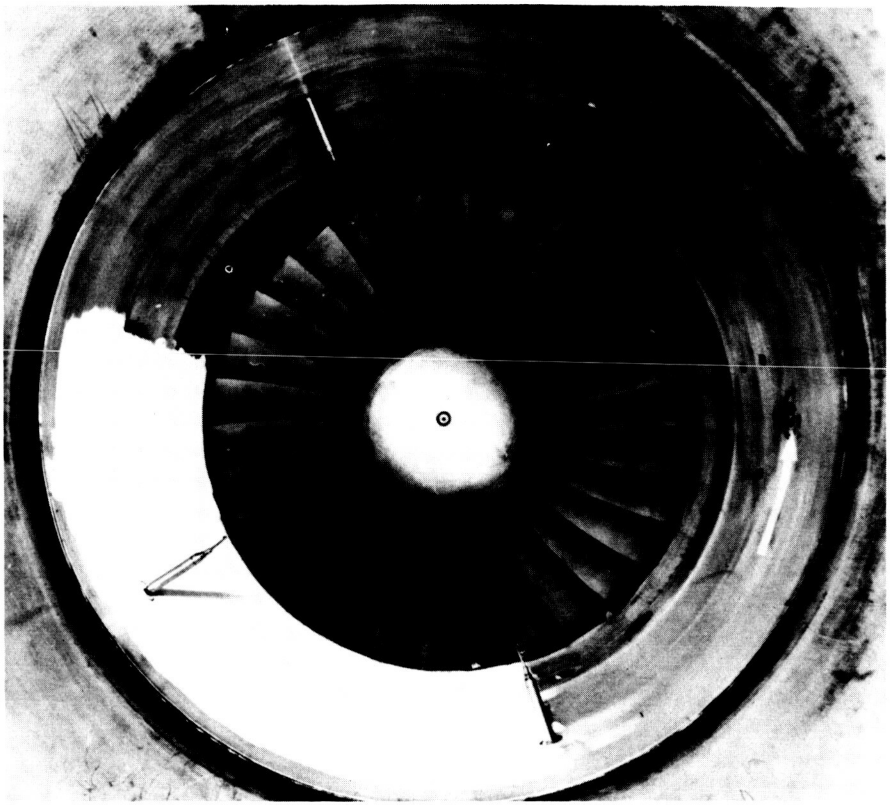

Fig. 1

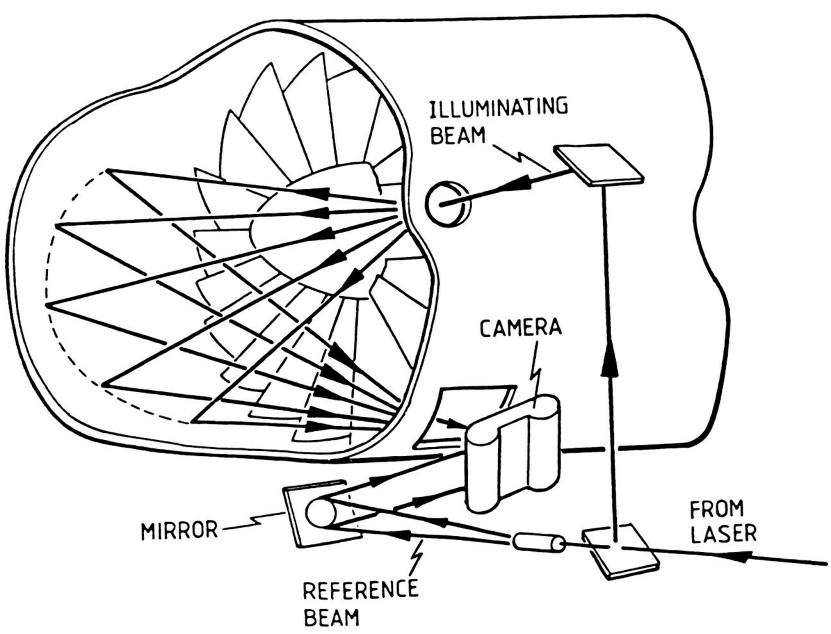
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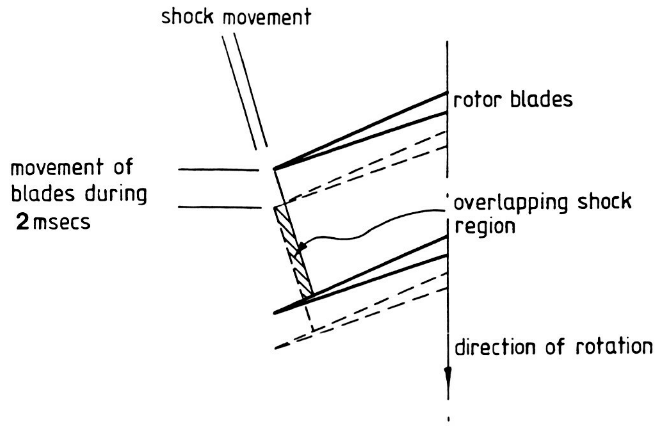
Fig. 2



Movement of a normal shock between two pulses with a 2msecs separation.

Fig. 3

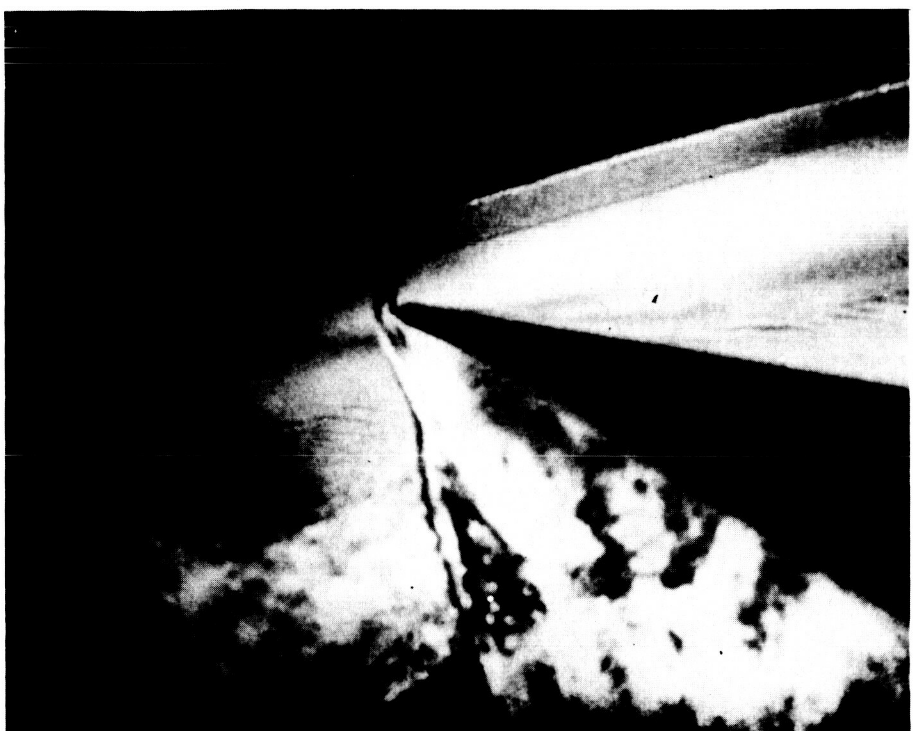


Fig. 4

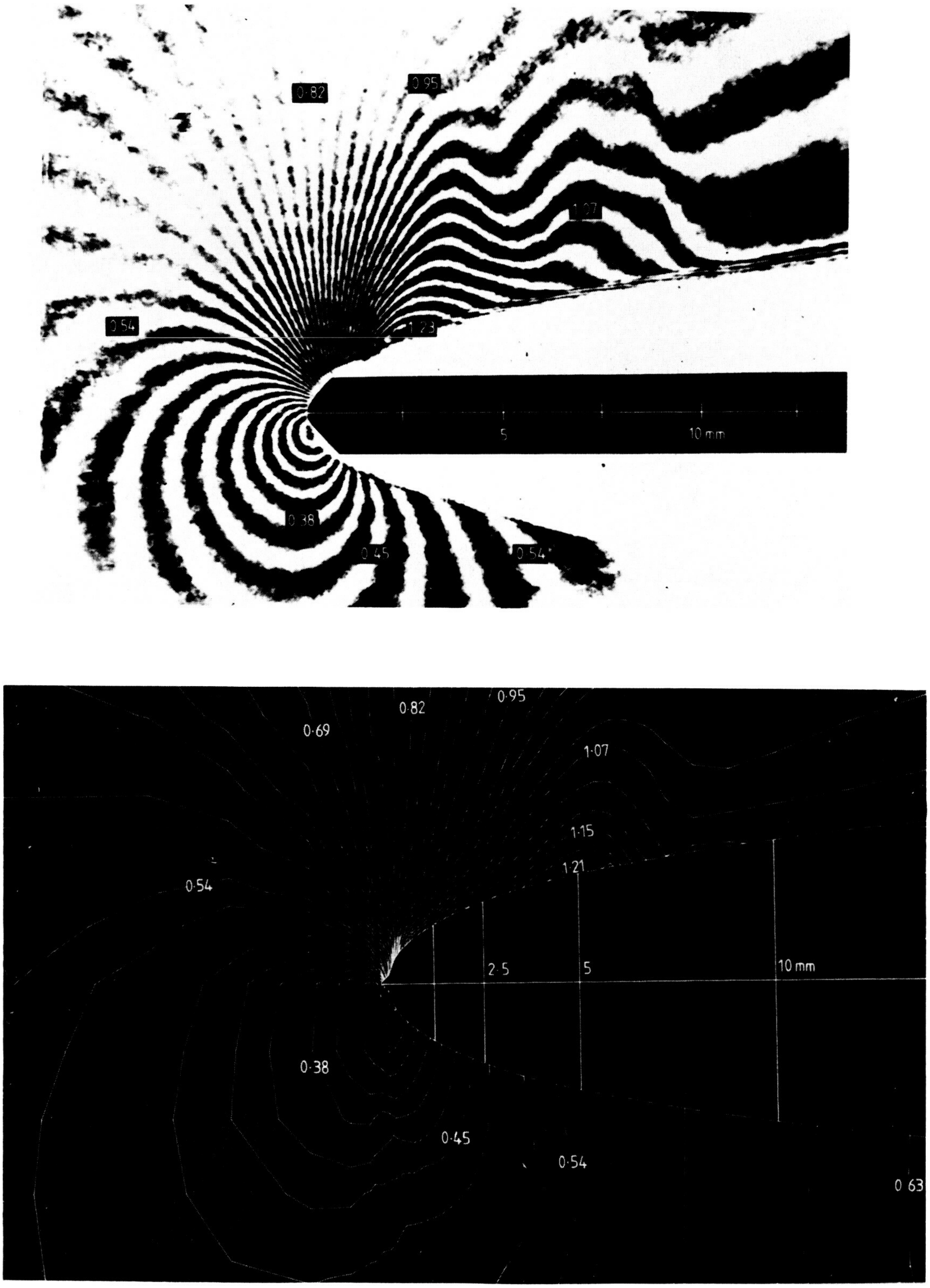

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Fig. 5

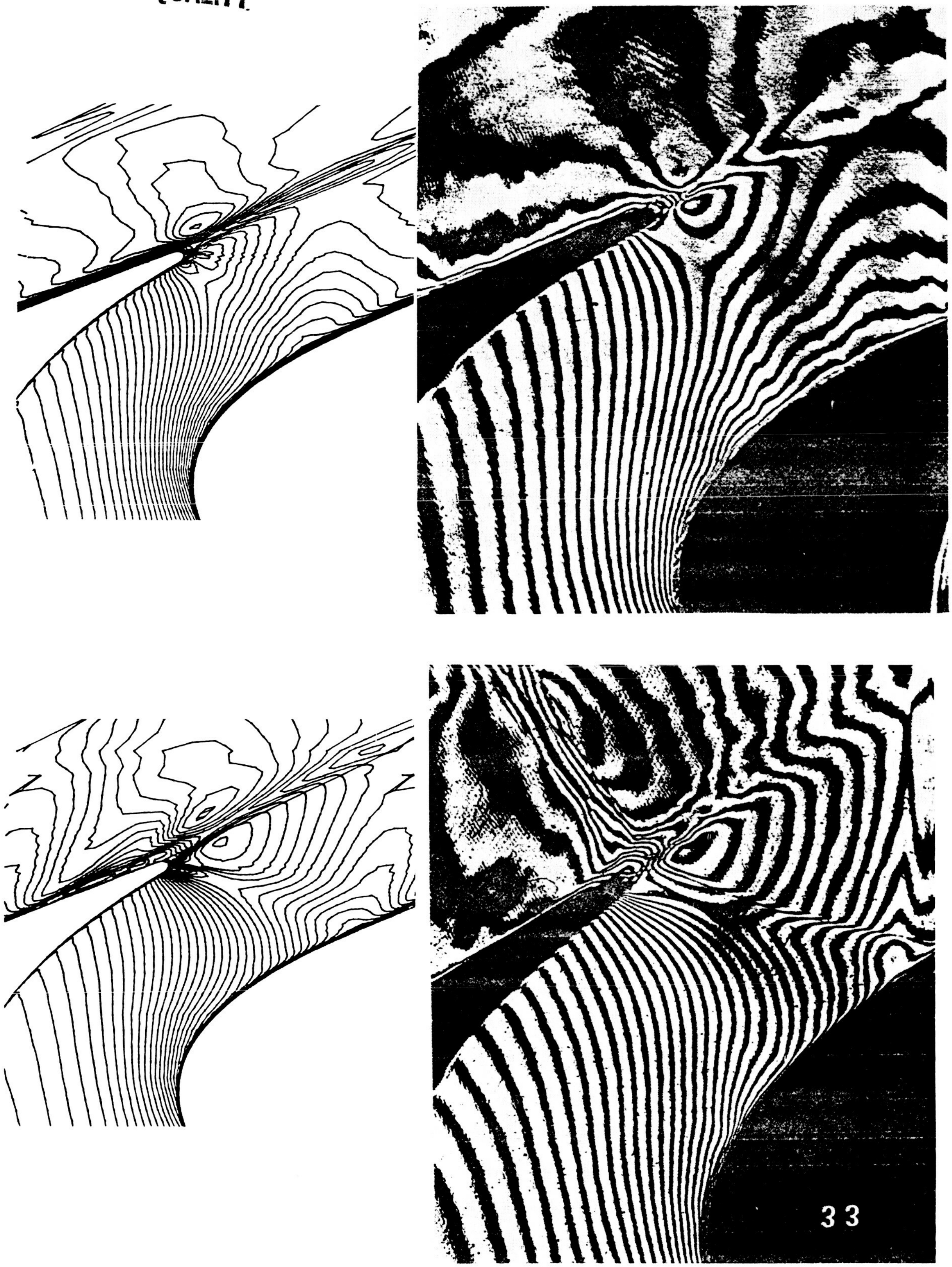


Fig. 6

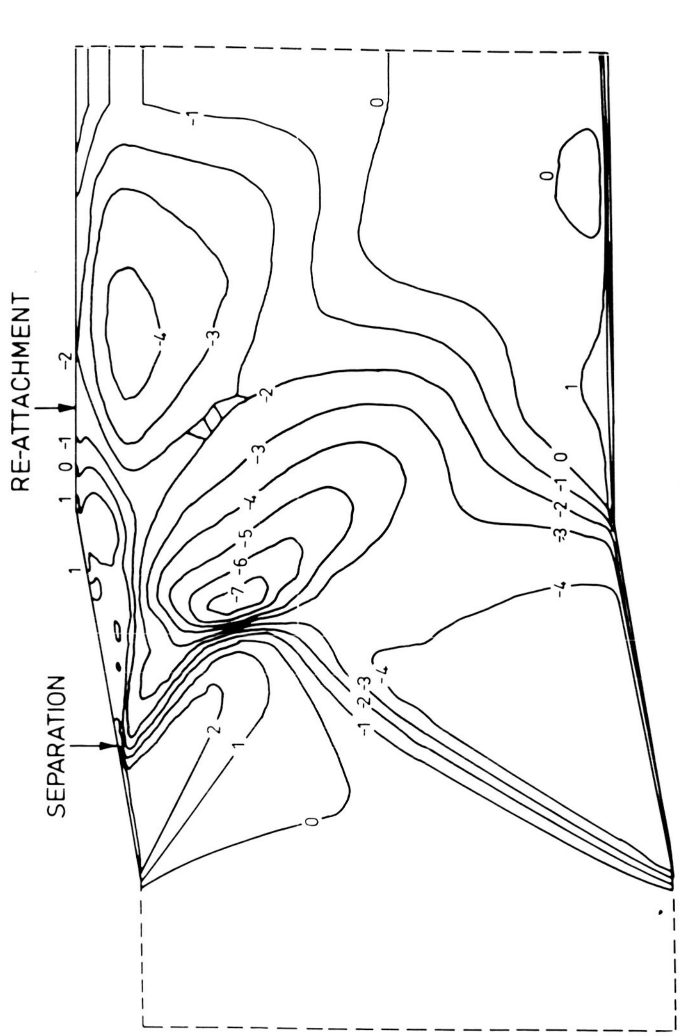


Fig. 7

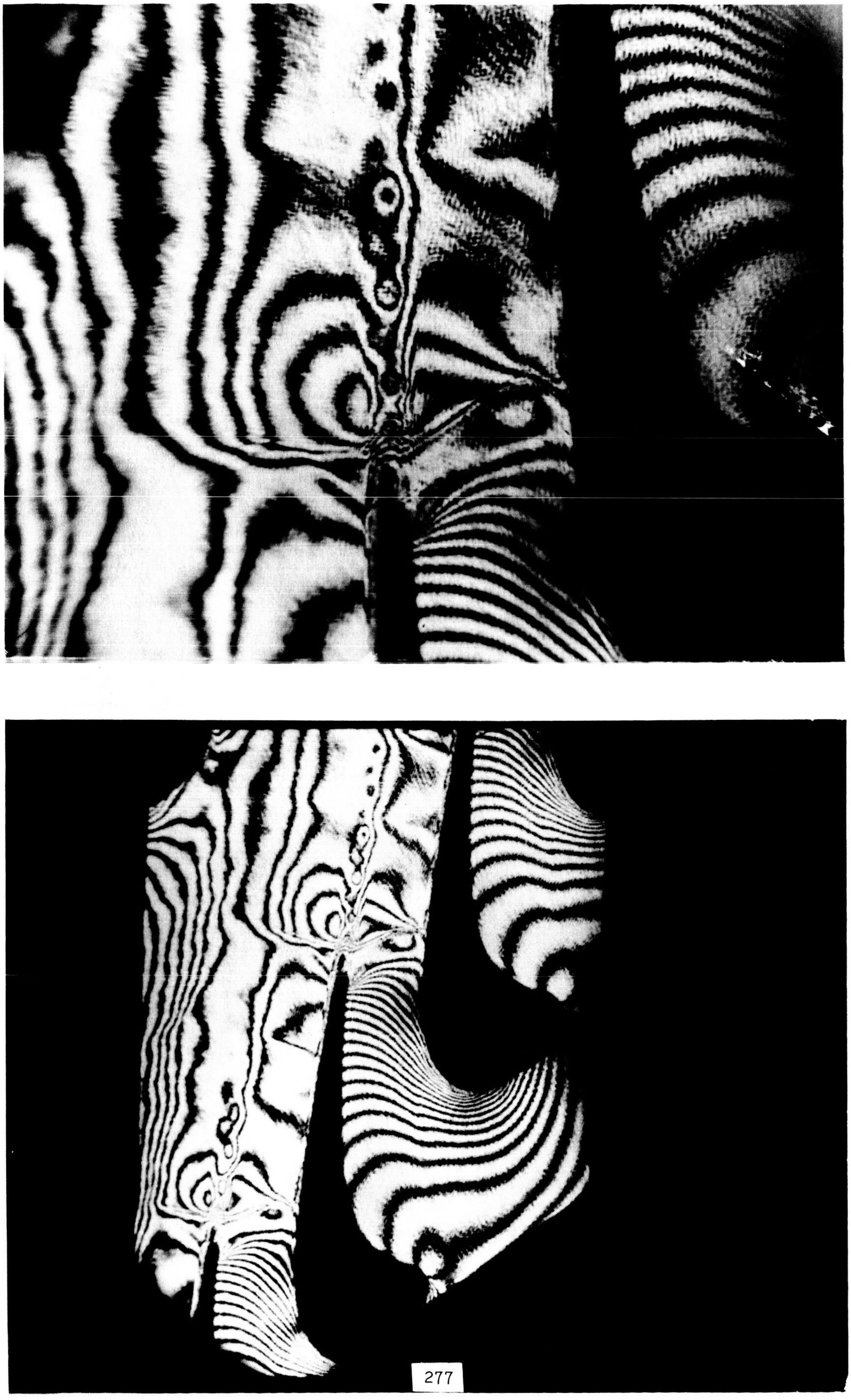
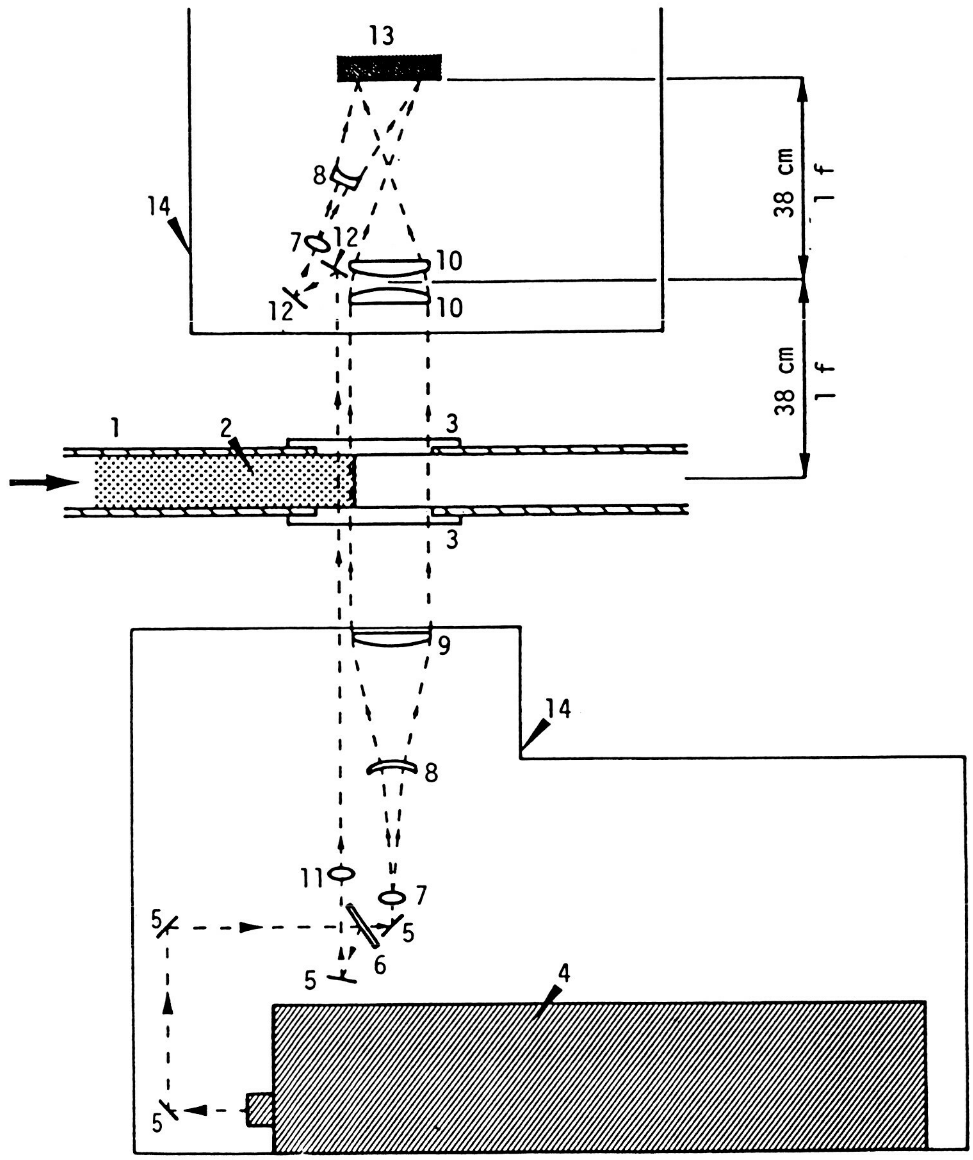


Fig. 8



1	Sidewalls of the Laval Nozzle	8	Negative lenses
2	Trailing edge model	9	Large aperture collimating lens
3	Perspex vindows	10	Large aperture plano-convex lenses
4	Pulse Laser (J.K.)	11	Collimating lens
5	Dielectrically coated mirrors	12	Mirrors
6	50% beam splitter	13	Holographic plate
7	Microscope objective x5	14	EPFL optical table

2-D (two dimensional) Holographic System EPFL 1984

Fig. 9

Fig. 10

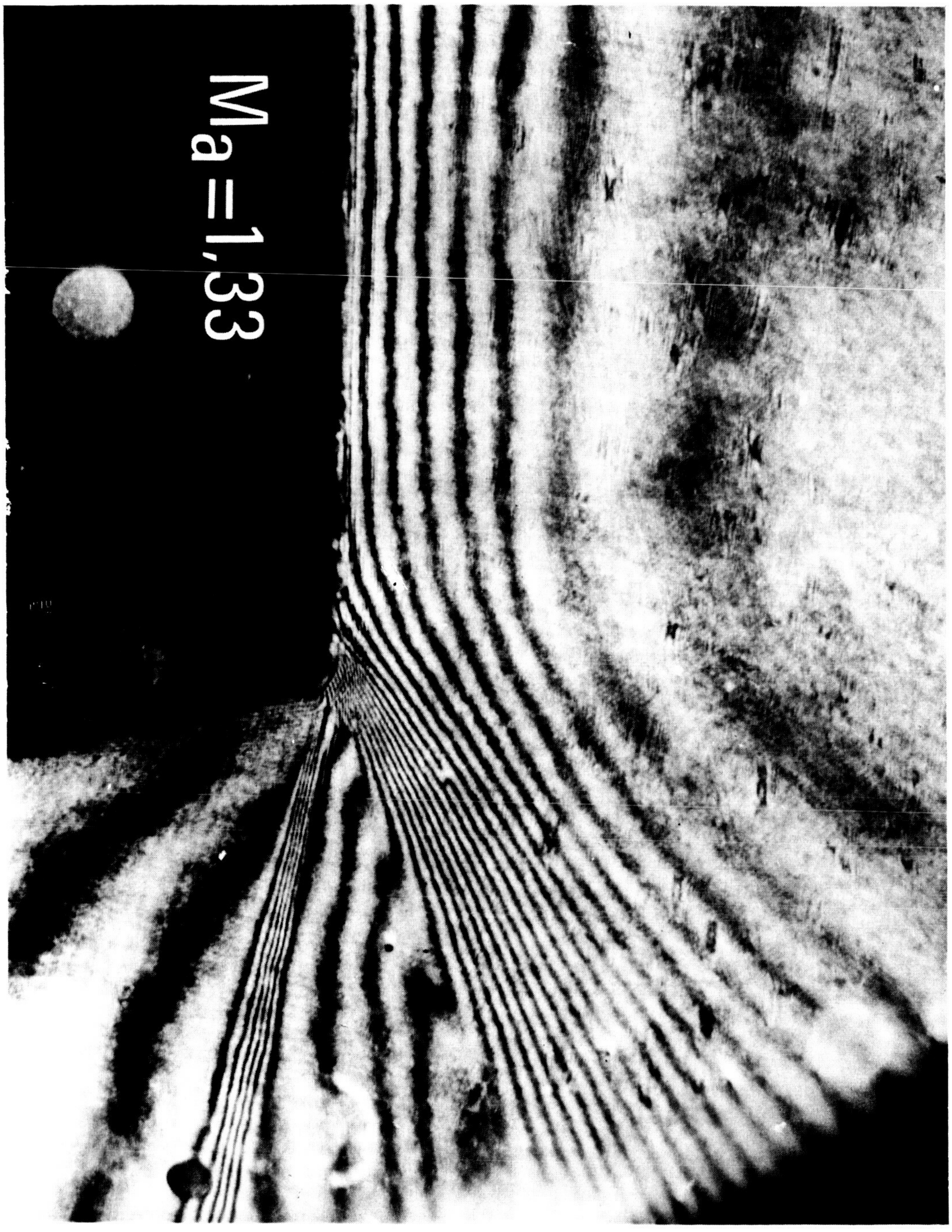


Fig. 11

Fig. 12

Fig. 13

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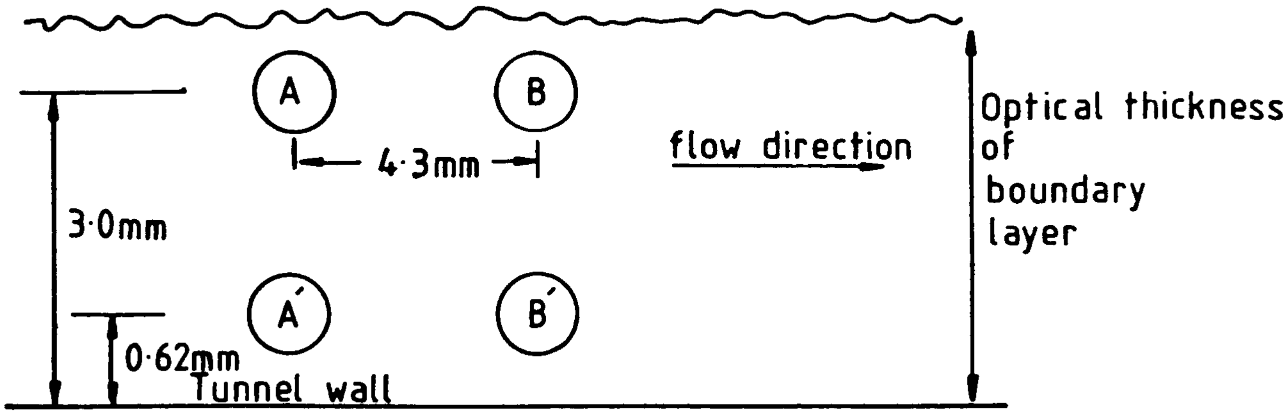
Fig. 15

Fig. 16

Fig. 17



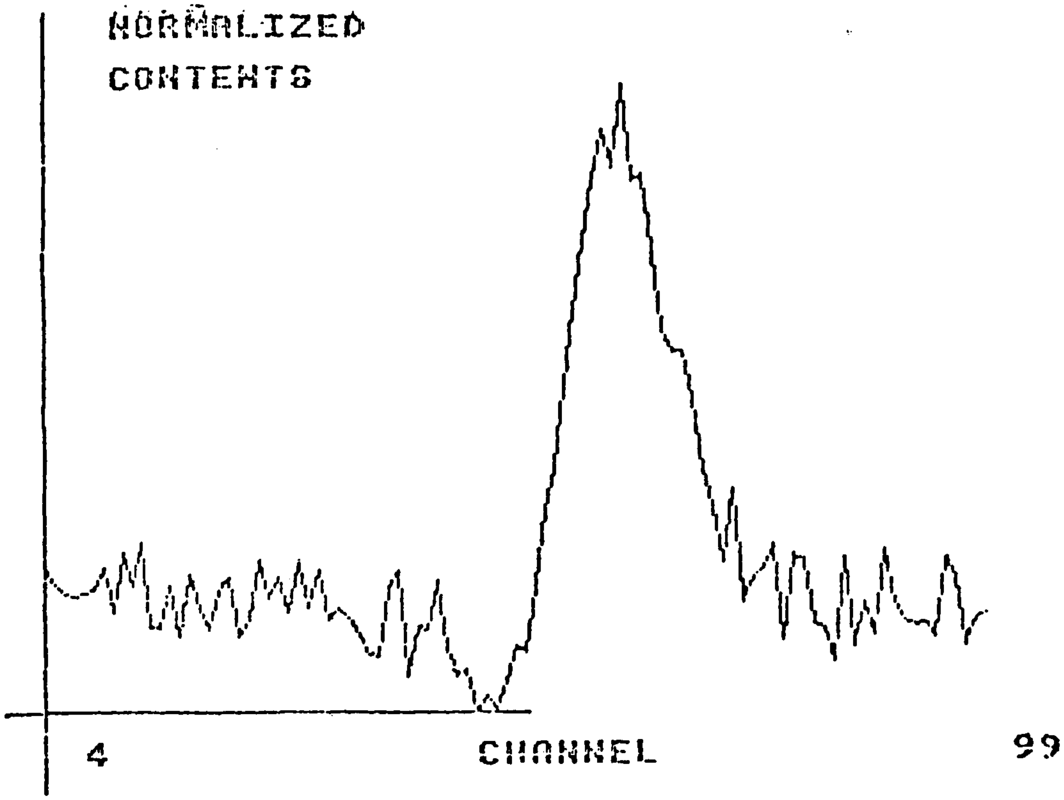
A×B cross-correlation 3·0 mm into boundary layer

A′×B′ cross-correlation 0·6 mm into boundary layer

Detector positions for cross-correlation of boundary layer structures

Fig. 18a

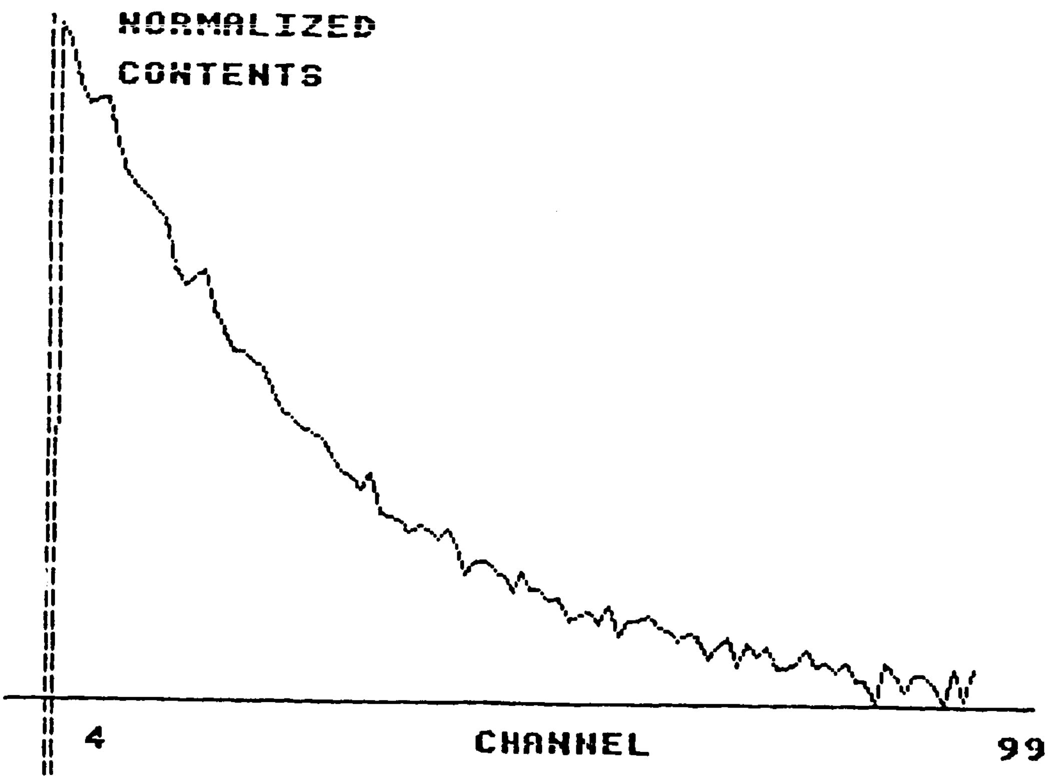
T = 20 μsecs.



CROSS CORRELATION MEASUREMENTS TAKEN 3.0 mm INTO BOUNDARY LAYER

Fig. 18b

T = 10 μsecs.



AUTOCORRELATION FUNCTION IN BOUNDARY LAYER DOWNSTREAM OF STEADY SHOCK

Fig. 18c

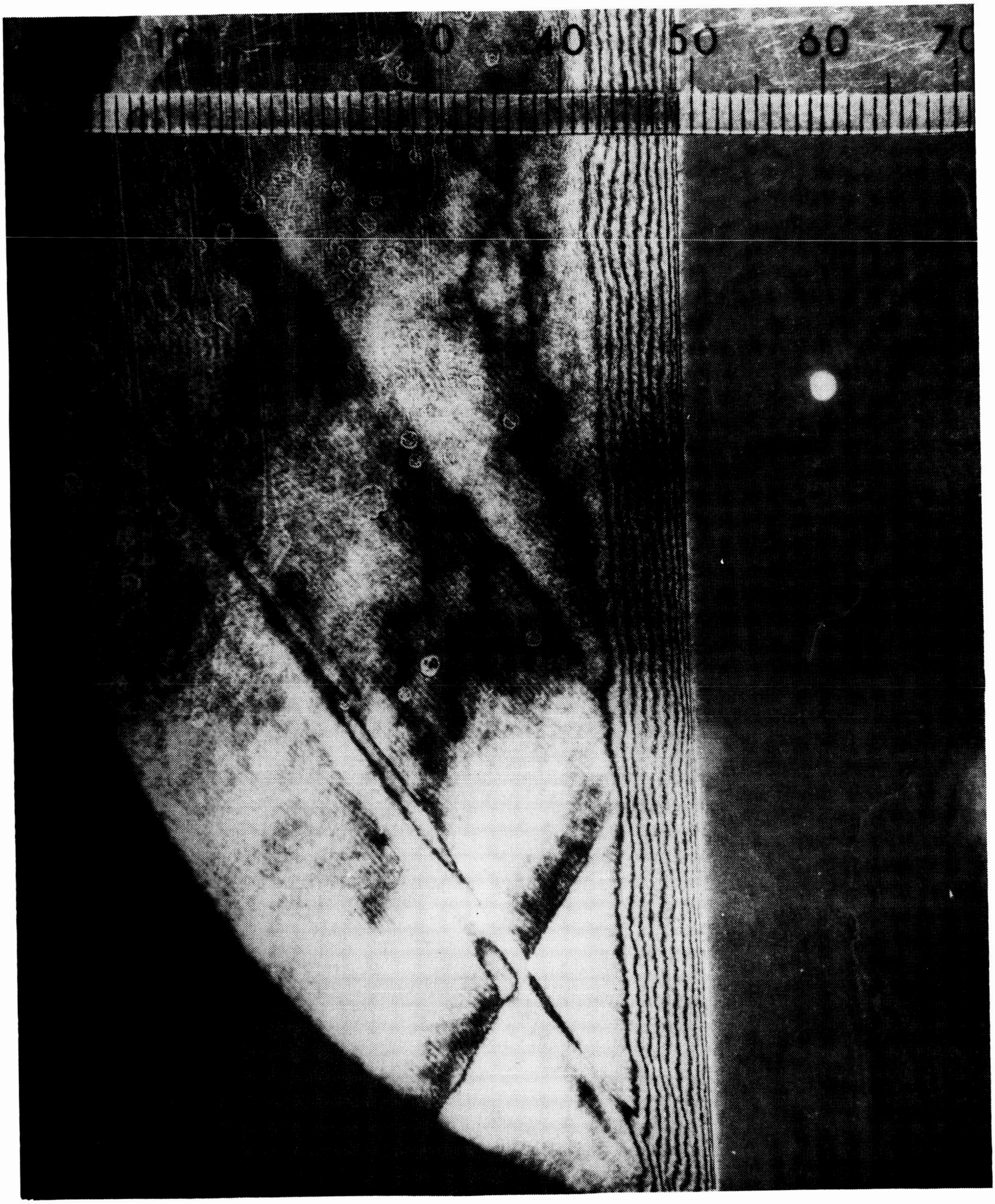


Fig. 19

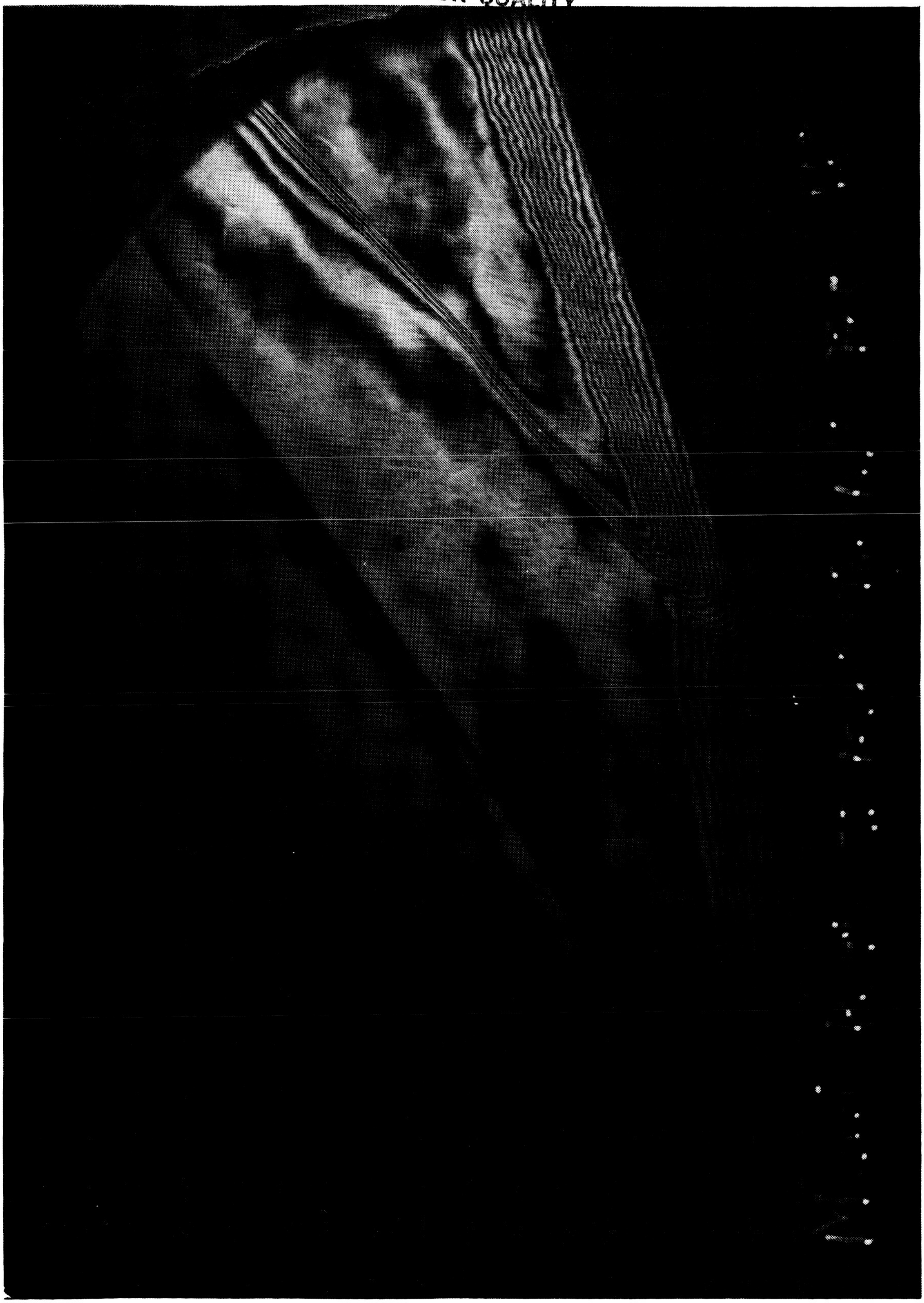


Fig. 20

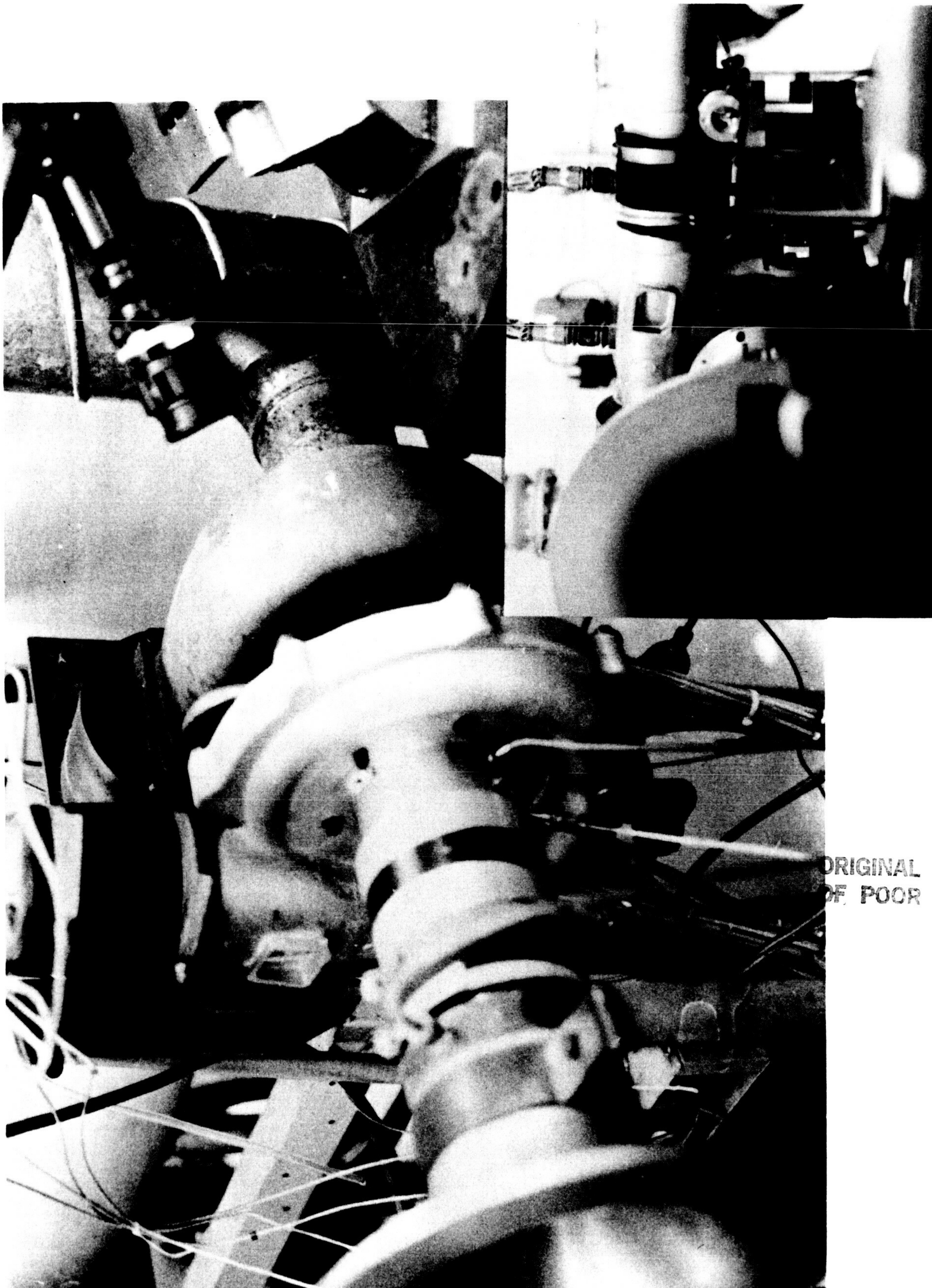


Fig. 21

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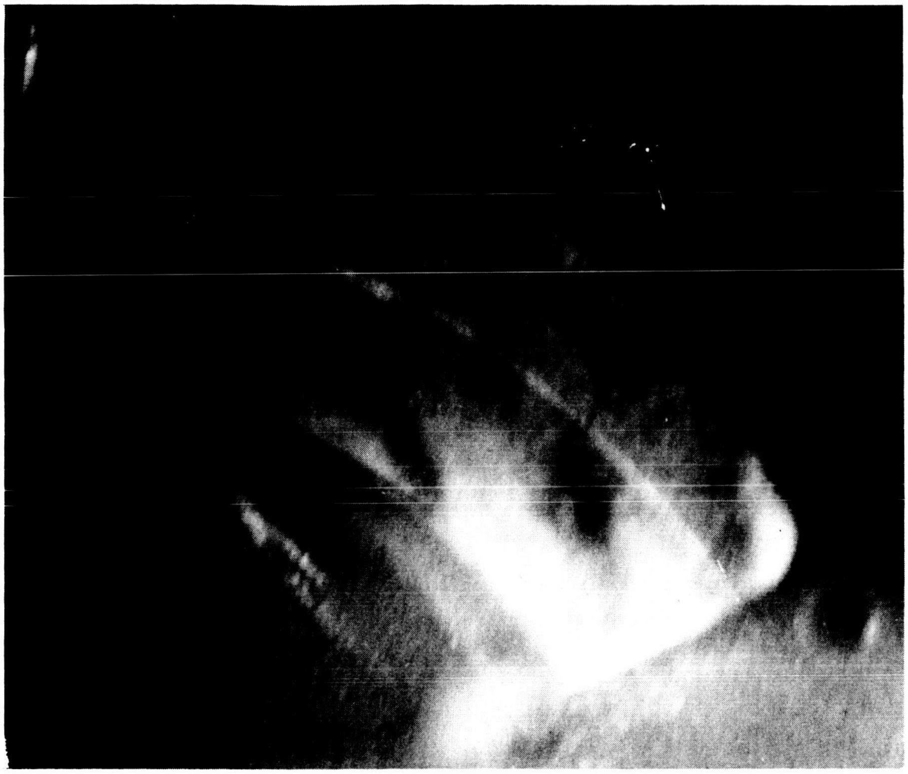

Fig. 22 Photographic reconstruction, made from a white light copy hologram, showing the vortex structure in the diffuser